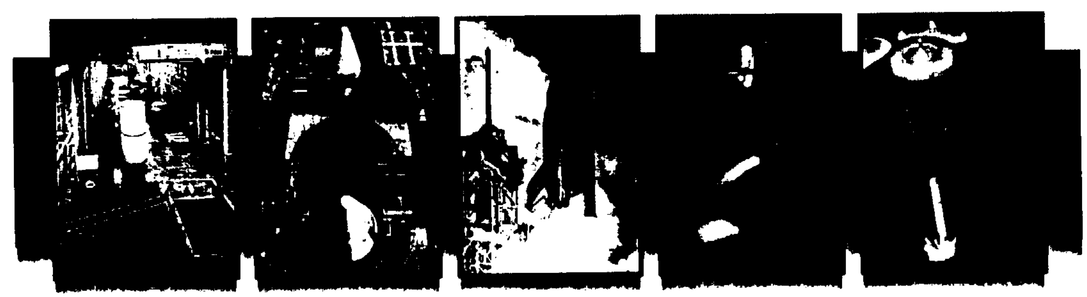
AIAA RSRM Short Course, July 2002, Indianapolis, Indiana

Space Shuttle Five-Segment Booster



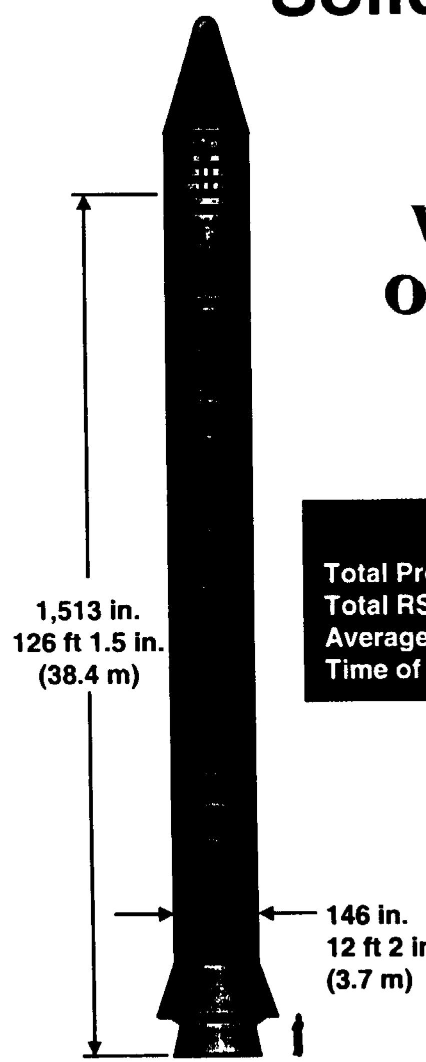
THIOKOL PROPULSION

Presented by:
Stanley R. Graves
Director, RSRM Engineering
ATK Thiokol Propulsion

020305ppt

FIVE SEGMENT BOOSTER

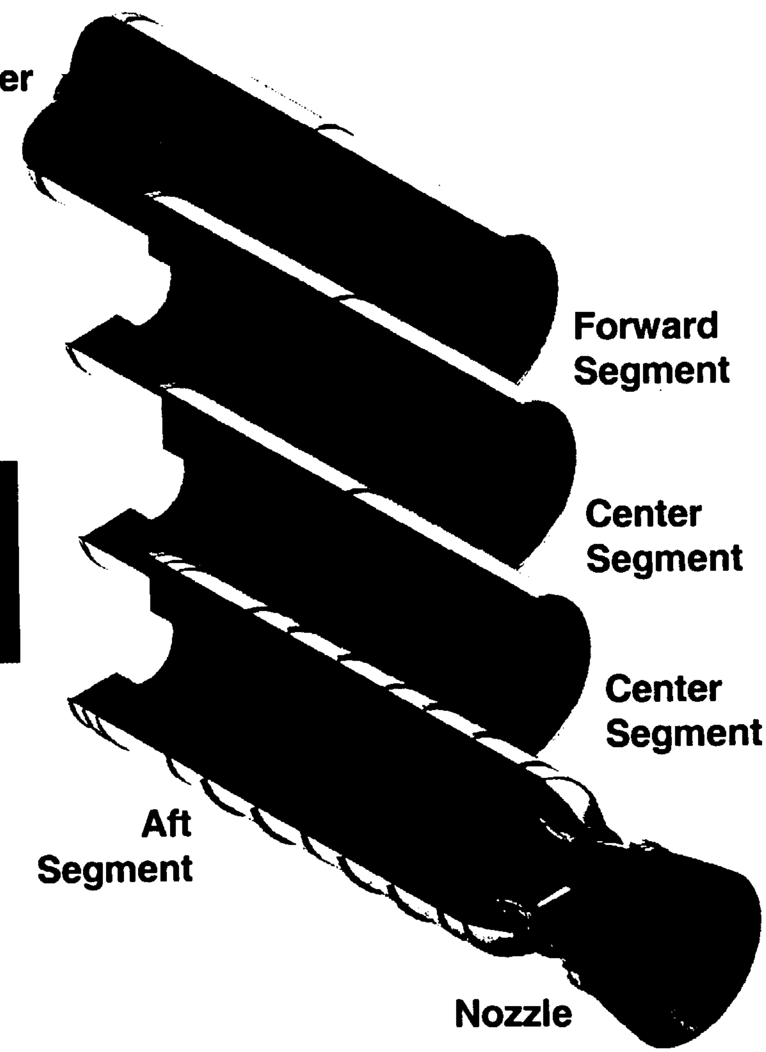
Space Shuttle Four-Segment Reusable Solid Rocket Motor (RSRM)



WORLD'S LARGEST OPERATIONAL SOLID ROCKET MOTOR

Space Shuttle RSRM

Total Propellant Weight:	1,107,000 lb	(503,000kg)
Total RSRM Weight:	1,256,000 lb	(570,000 kg)
Average Thrust:	2,590,000 lbf	(11,530,000 N)
Time of Burning:	123.4 sec	



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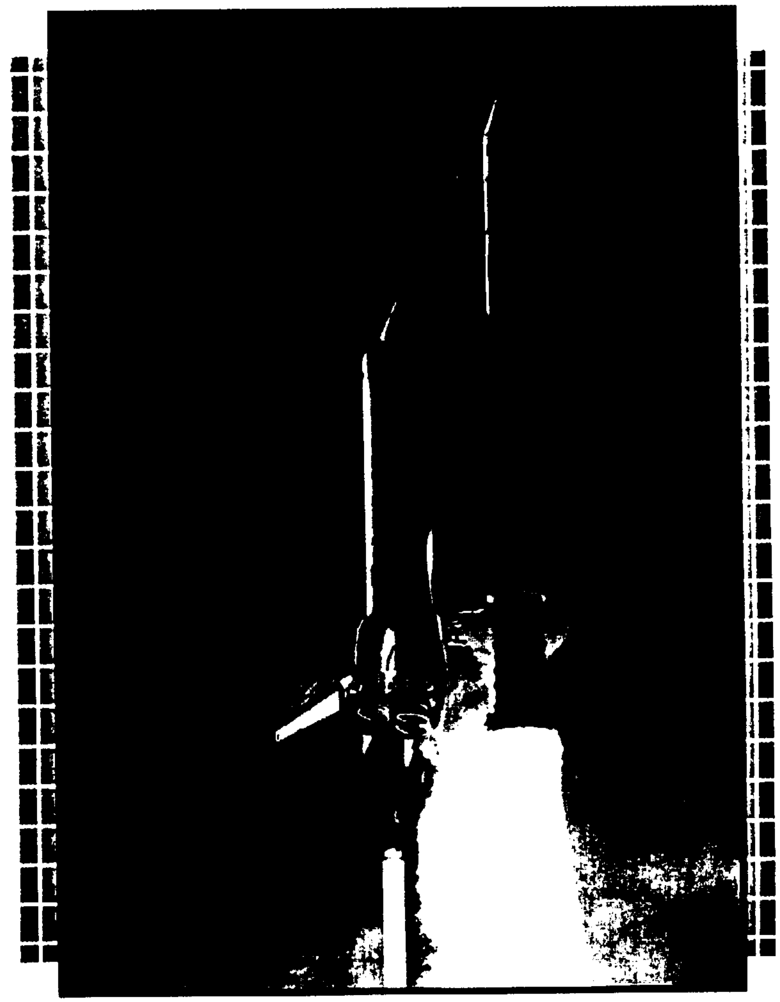
RSRM History

- **Program start: 1974**
- **First static test: 1977**
- **First flight: April 12, 1981**
  - 25 flights: 1981 to 1986
- ***Challenger* disaster: January 28, 1986**
- **Redesign activity: 1986 to 1988**
  - Improved field joints, igniter joints, nozzle-to-case joint, and nozzle ablatives
- **Return to flight: September 29, 1988**
  - 85 RSRM flights:1988 to 2002
- **28 years: 259 total motors flown or tested**
  - 39 static tests
  - 220 flight motors

Return to Flight (STS-26)

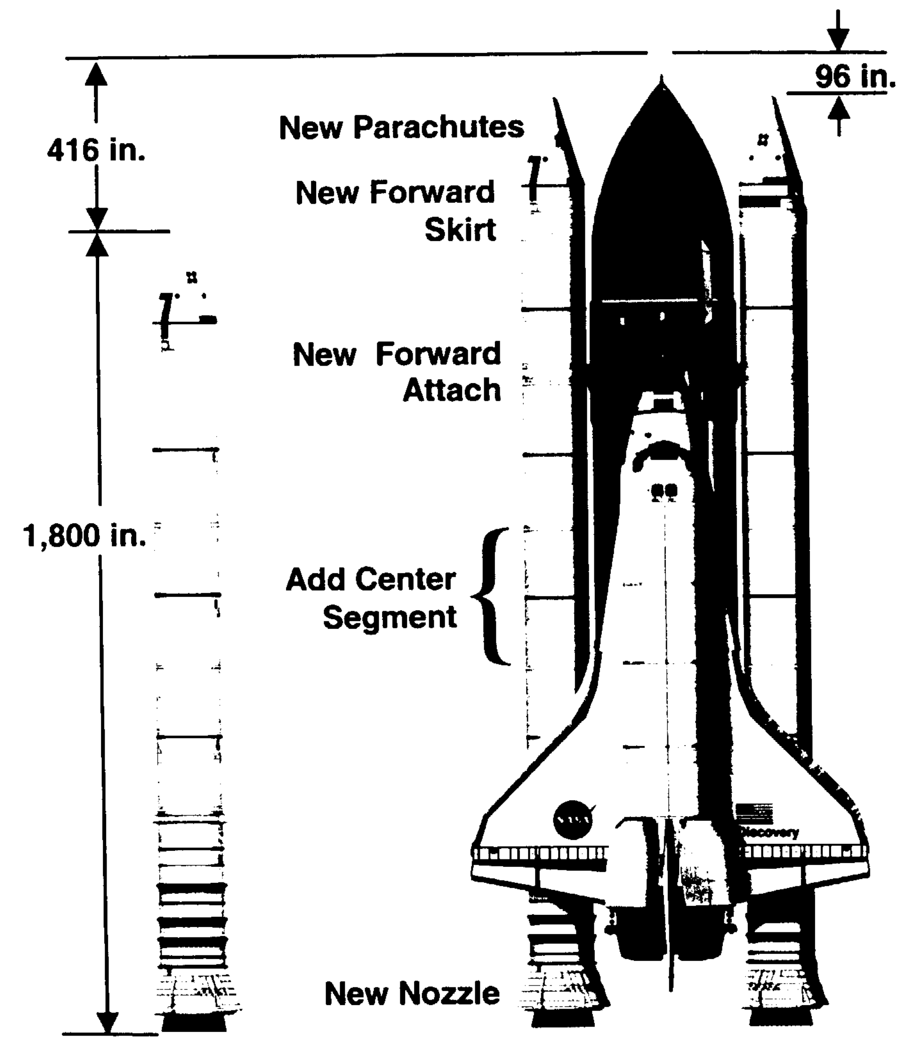
Future Plans: Five-Segment Booster (FSB)

- **NASA is considering upgrading the Space Shuttle by adding a fifth segment to the current four-segment solid rocket booster**
- **Enhance Space Shuttle capability**
  - Eliminate Return to Launch Site (RTLS) or Trans-Atlantic Landing (TAL) abort modes
  - Achieve Abort-to-Orbit (ATO) with single engine out off the pad
  - Orbiter space station Alpha payload increased to 40,000 lb
  - Enable crew escape module and other Shuttle system reliability and safety upgrades
  - Reduce main engine throttle settings
- **Potential boost propulsion for heavy-lift vehicle**

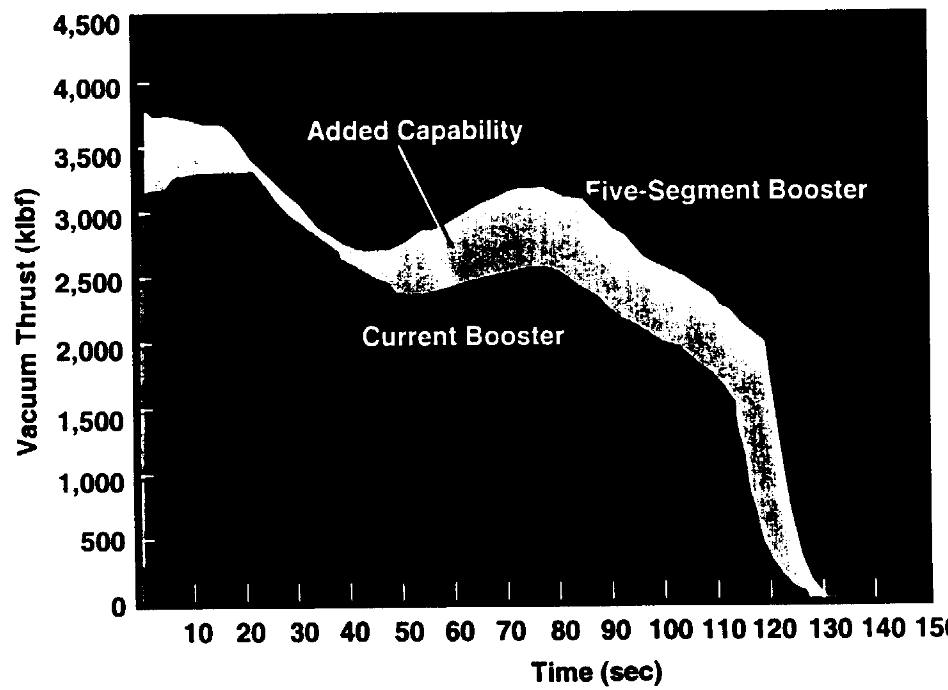


FIVE SEGMENT BOOSTER

Four-Segment vs. Five-Segment Booster



Four-Segment Booster Five-Segment Booster



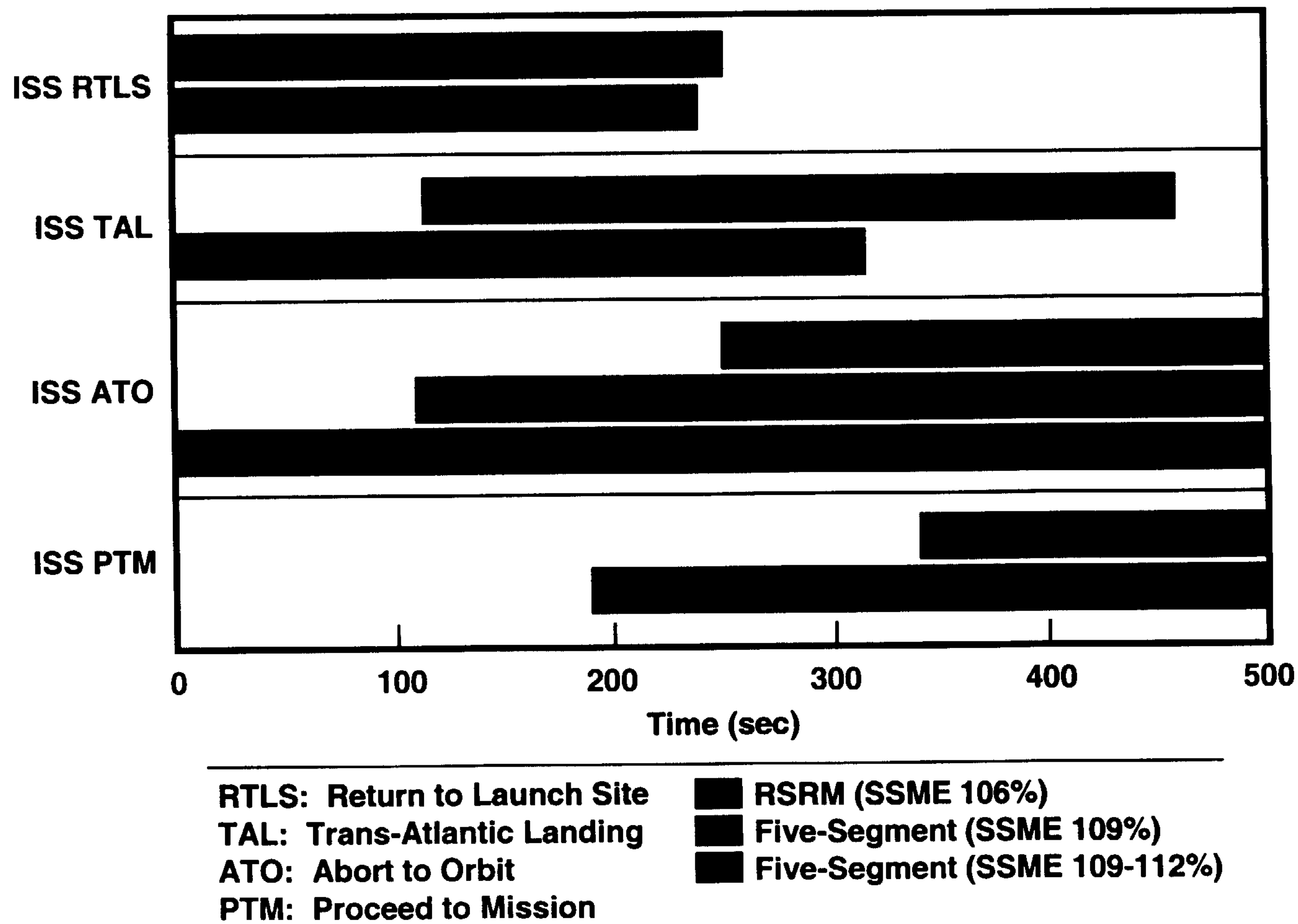
Booster Performance

	5-Segment	4-Segment
Max Thrust (lbf)	3,800,000	3,330,000
Max Pressure (psia)	1016	1016
Burn Time (sec)	129.6	123.4

FIVE SEGMENT BOOSTER

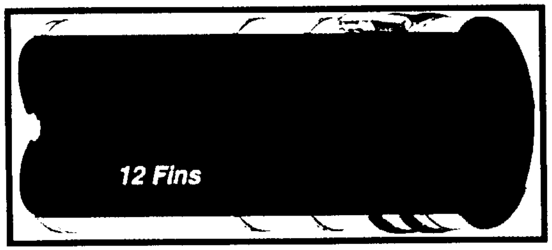
Abort Modes (one SSME out) Study Results

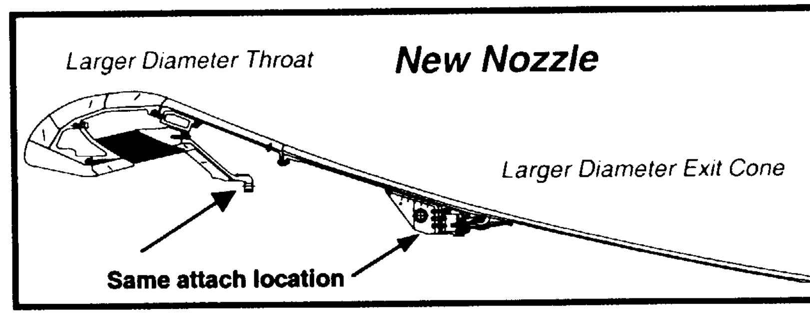
- Achieve ATO from pad at 109 - 112% SSME throttle with adequate performance margins

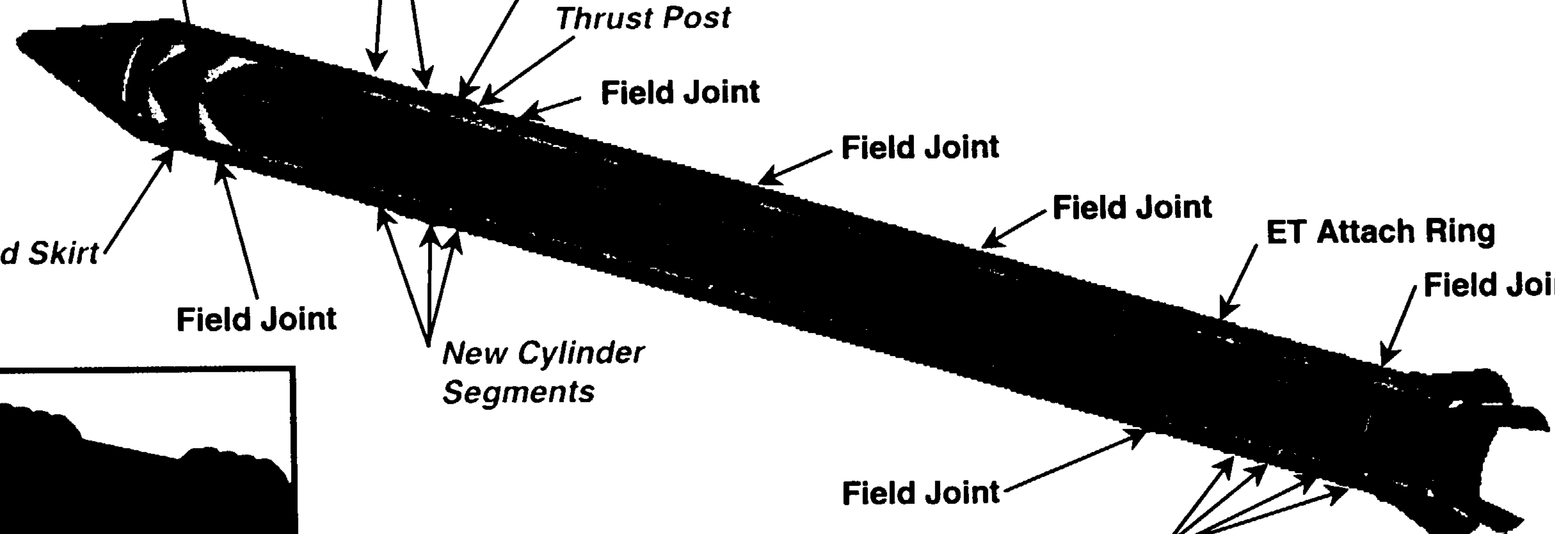


FIVE SEGMENT BOOSTER

Five-Segment Booster





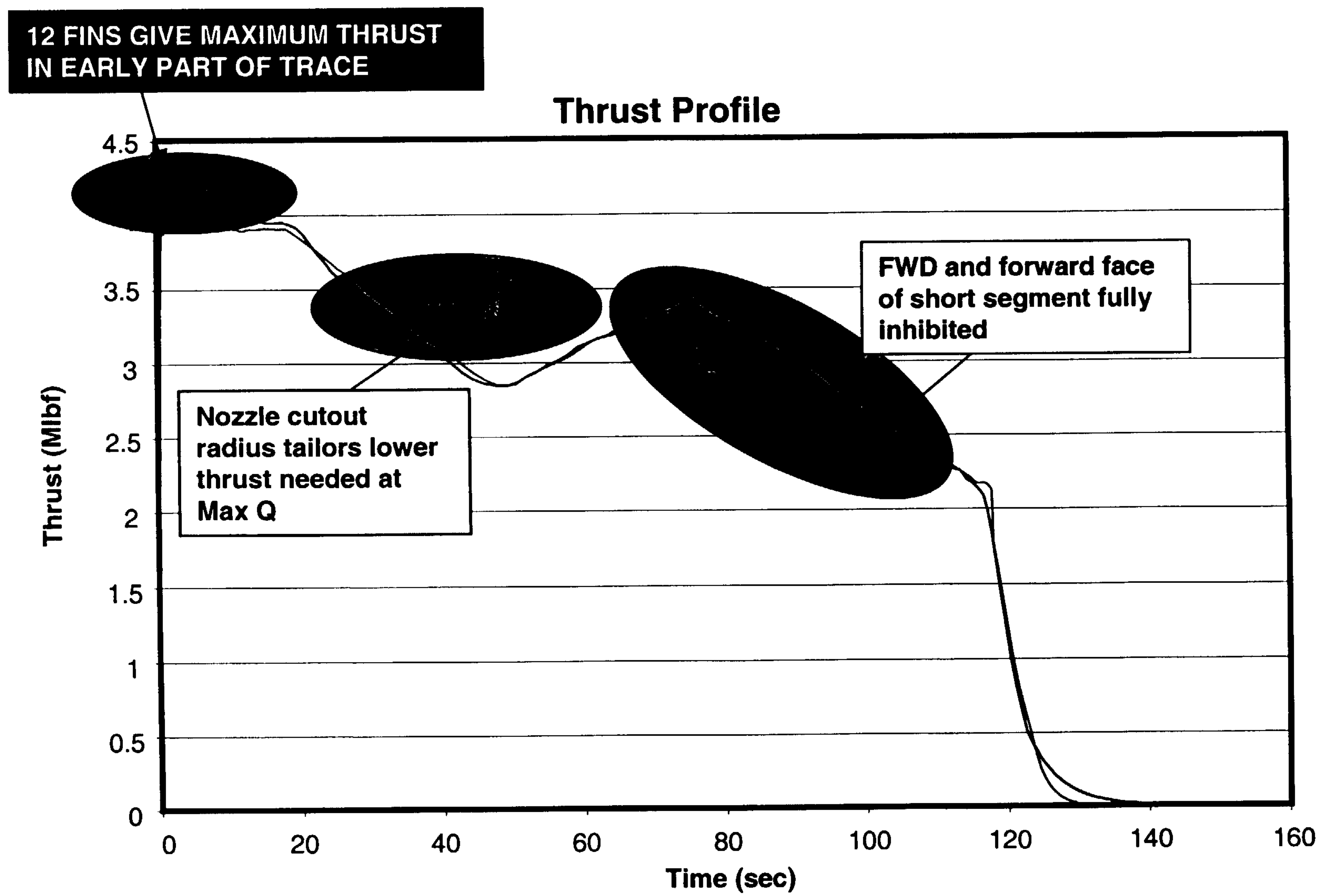


Thrust Post

Changes noted in italic

FIVE SEGMENT BOOSTER

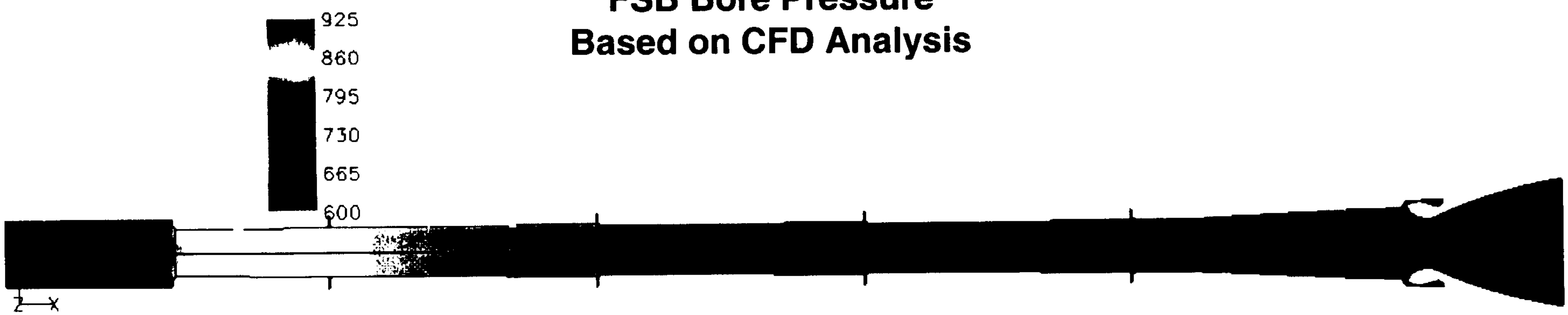
FSB Grain Design



FIVE SEGMENT BOOSTER

Pressure Drop Down the Bore at Ignition

FSB Bore Pressure
Based on CFD Analysis

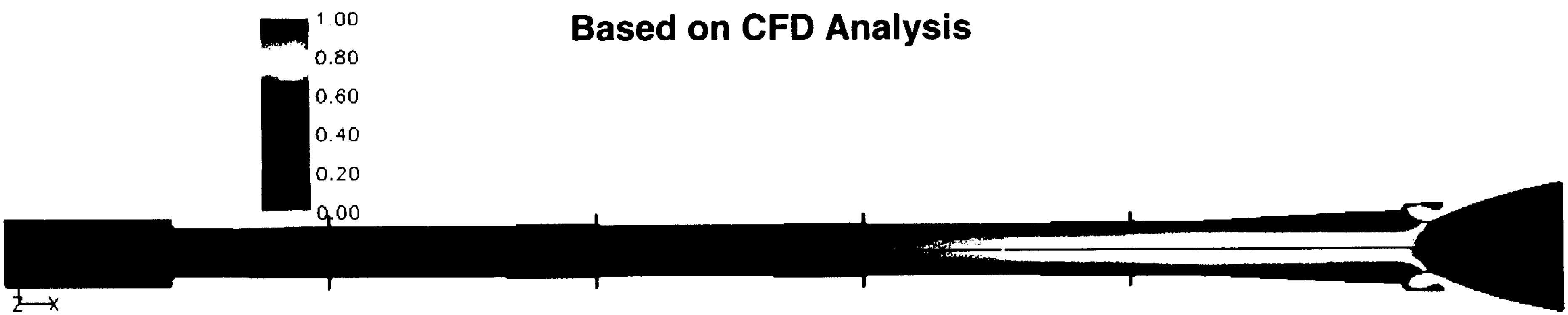


FSB REPRESENTS ~115 PSIA INCREASE IN RSRM STATIC PRESSURE DROP

FIVE SEGMENT BOOSTER

Mach Number Down the Bore at Ignition

FSB Bore Mach Number
Based on CFD Analysis



FSB REPRESENTS ~0.2 INCREASE IN RSRM CENTERLINE MACH NUMBER

FSB Design Issue: Erosive Burning

- **Concerns**
  - Solid rocket motor with high cross-flow velocities (high Mach number) susceptible to "erosive burning"
  - Burn rate enhancement due to erosive burning increases head-end pressure levels
    - Shuttle pressure trace reaches maximum head-end pressure during ignition
    - Erosive burning compounds operating pressure possibly affecting certified maximum expected operating pressure (MEOP)
  - Erosive burning difficult to predict
    - Current models are empirically derived, and based on small scale motors relative to FSB

ACCURATE EROSIVE BURNING PREDICTIONS REQUIRED FOR FSB

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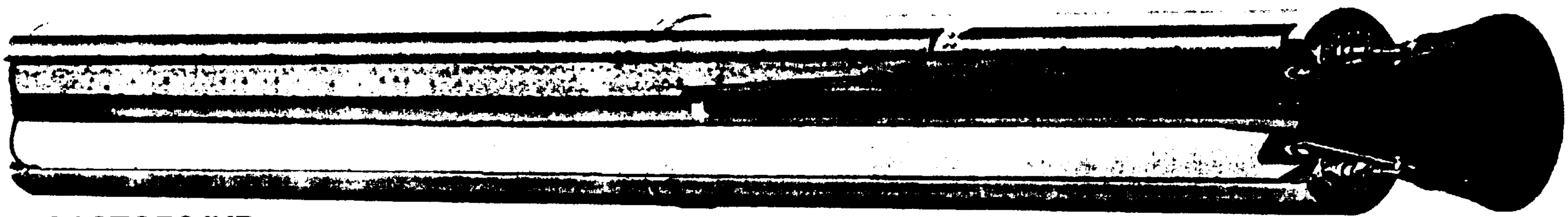
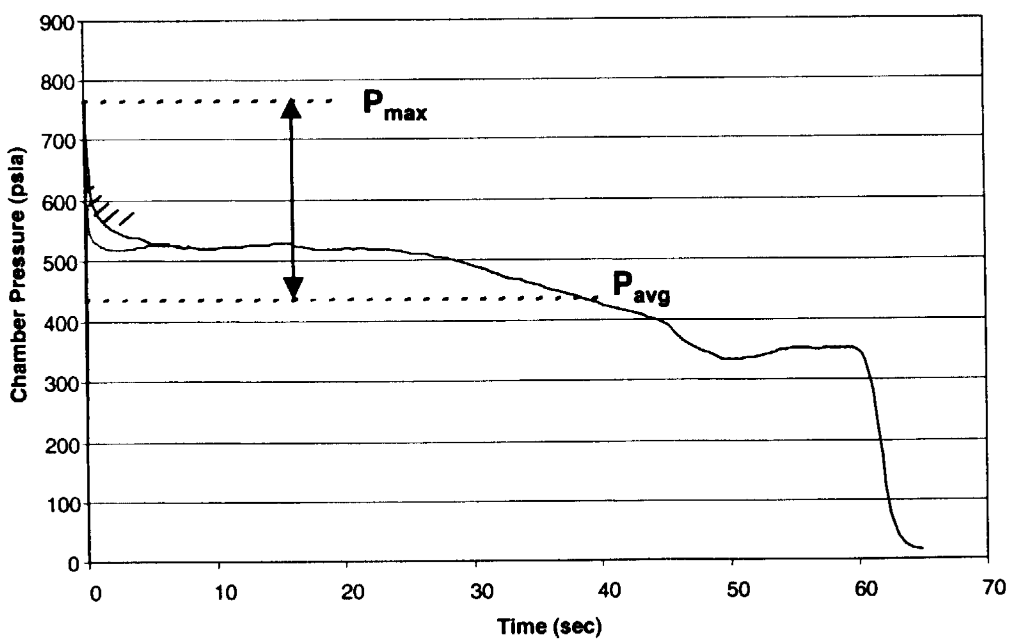
Enhanced Propellant Burn Rate



CASTOR® IVB



- **Large length to diameter ratios can lead to enhanced propellant burn rates**
- **There is a Mach number threshold above which enhanced burn rate predominates**
- **The enhanced burn rate is usually of short duration and repeatable**
  - Difficult to predict for new designs using current modeling techniques

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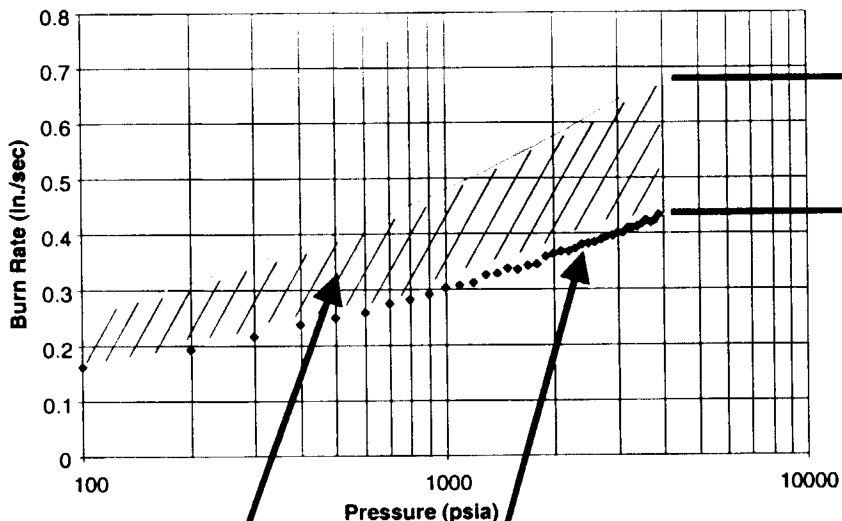
Drivers of Enhanced Propellant Burn Rate

Propellant Burn Rate



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- **Burn rate enhancement driven by internal environment**
- **Factors influencing enhanced burn rate**
  - Bulk fluid velocity
  - Mass flow rate
  - Motor geometry
    - L/D
    - Grain bore diameter
    - Nozzle throat diameter

FSB Erosive Burning Model Development

- **Approach**
  - Develop relationship between Mach number, pressure, and hydraulic diameter for propellants with different burn rates
    - Subscale tandem, segmented 5-in. CP test article designed
    - Test motors instrumented to measure propellant surface regression and pressure drop down the motor
    - Developed relationship between burn rate and mach number in subscale motor
  - Developed scale factors to adjust for motor size
    - Anchored model to CASTOR® IVB and RSRM
  - Plan to validate FSB erosive burning scale factors using a full-scale 5-segment RSRM static test (ETM-3) in July 2003

FIRST STEP IN MODEL DEVELOPMENT AND VALIDATION

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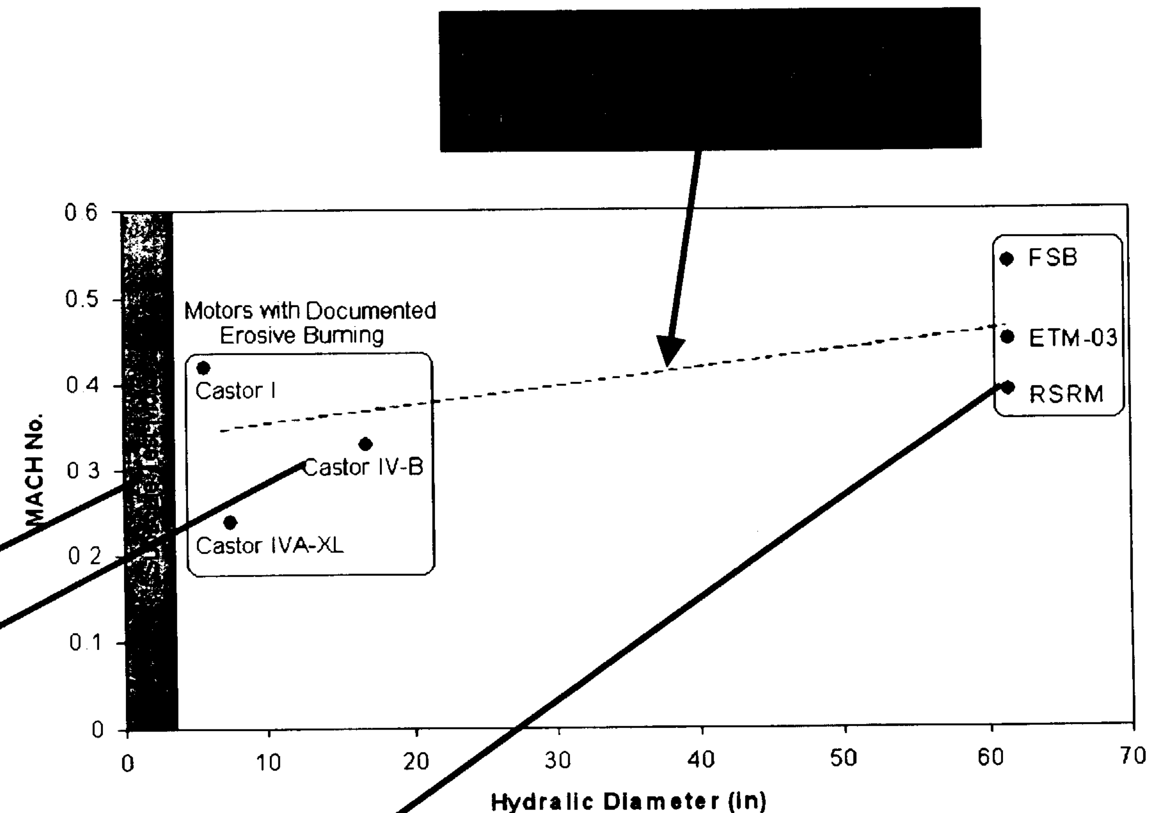
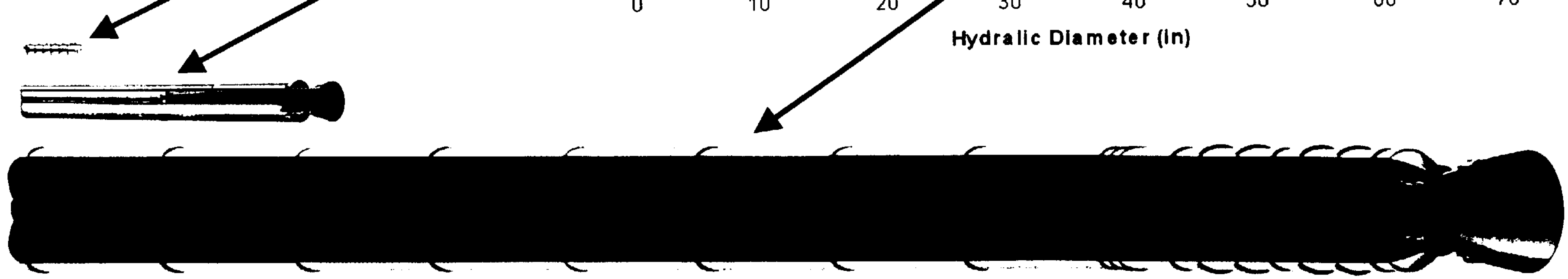
Modeling Approach

- **Use existing motor data to scale subscale motor data**
  - Enable development of a scaleable erosive burning model without a midsize test motor
- **Provide an accurate prediction for FSB**





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Subscale Motor Hardware Overview

- **Subscale test motor configuration**
  - Six tandem 5-in.center-perforated (CP) motors
  - Bore/throat diameter controls Mach number
  - Number of segments controls motor chamber pressure
- **Instrumentation/signal acquisition**
  - Signal transmission
    - Ultrasonic signal enhanced through impedance matching of materials
    - Acoustic lens to reduce signal scatter on curved propellant surface
  - Noise reduction
    - Elimination of standing wave noise
    - Return signal synchronized with reflection of propellant gum stock interface

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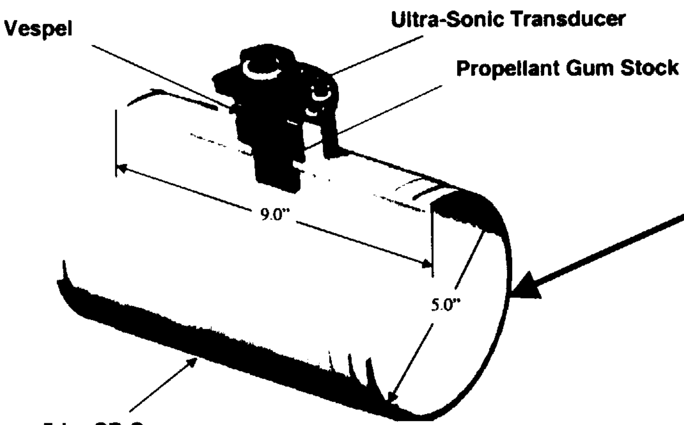
Hardware Configuration



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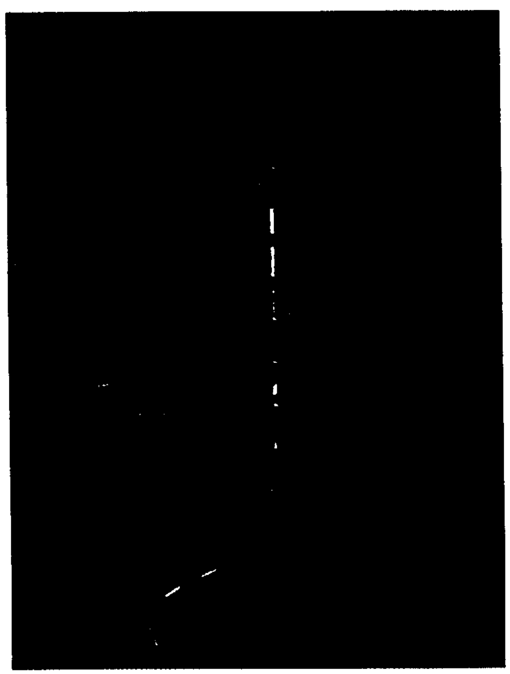
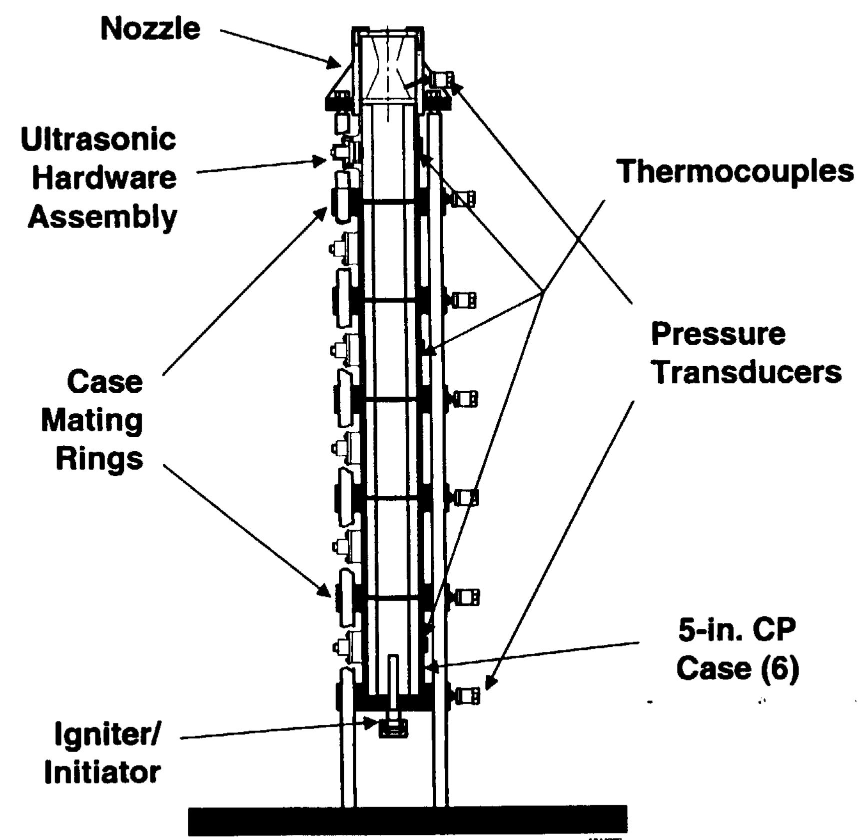
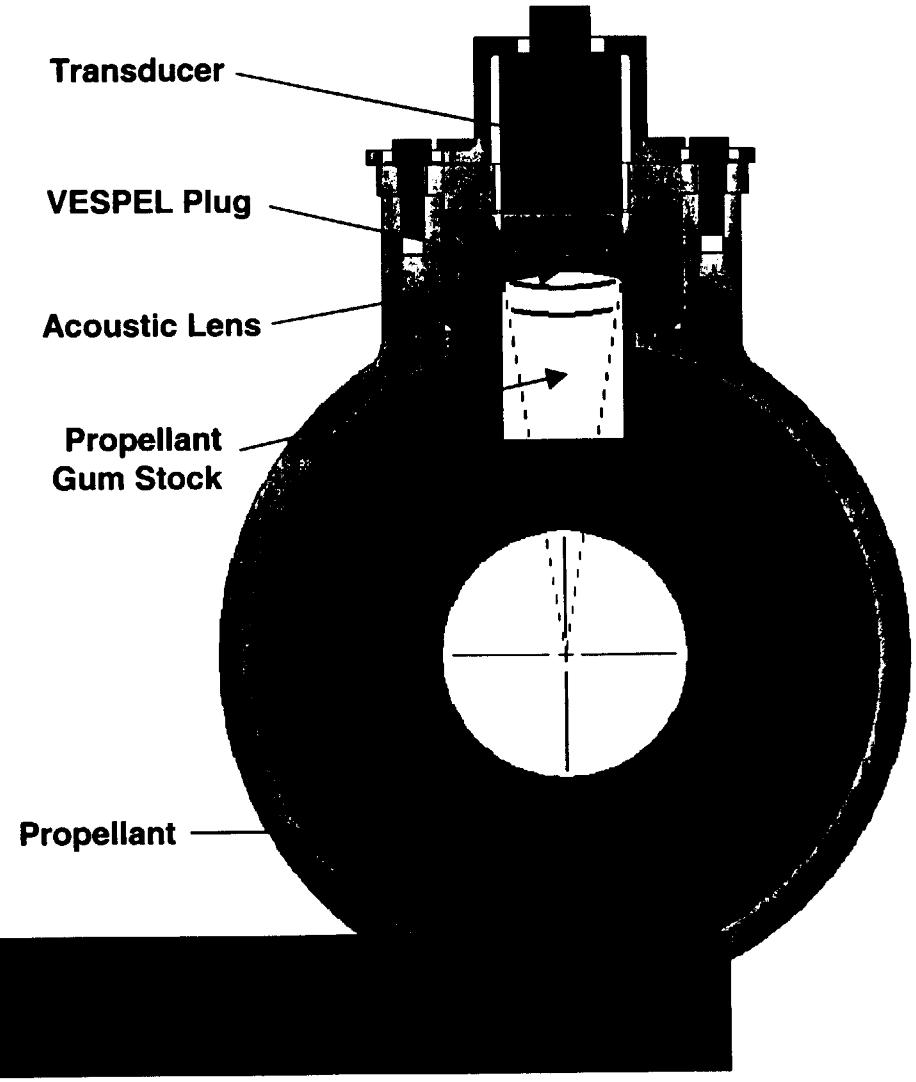




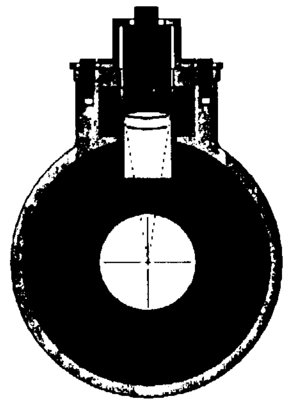
Ultrasonic Instrument Configuration

- **Acoustic stack**
- **VESPEL**
  - Provides an acoustic window through the case wall
  - Supports motor operating pressure
- **Acoustic lens**
  - Curvature on the VESPEL surface about the motor centerline to focus the signal on the propellant bore surface
  - Minimizes signal scatter
- **Propellant gum stock**
  - Intermediate acoustic impedance material
  - Propellant without solids
- **Propellants**
  - CASTOR®, ETM-3, RSRM

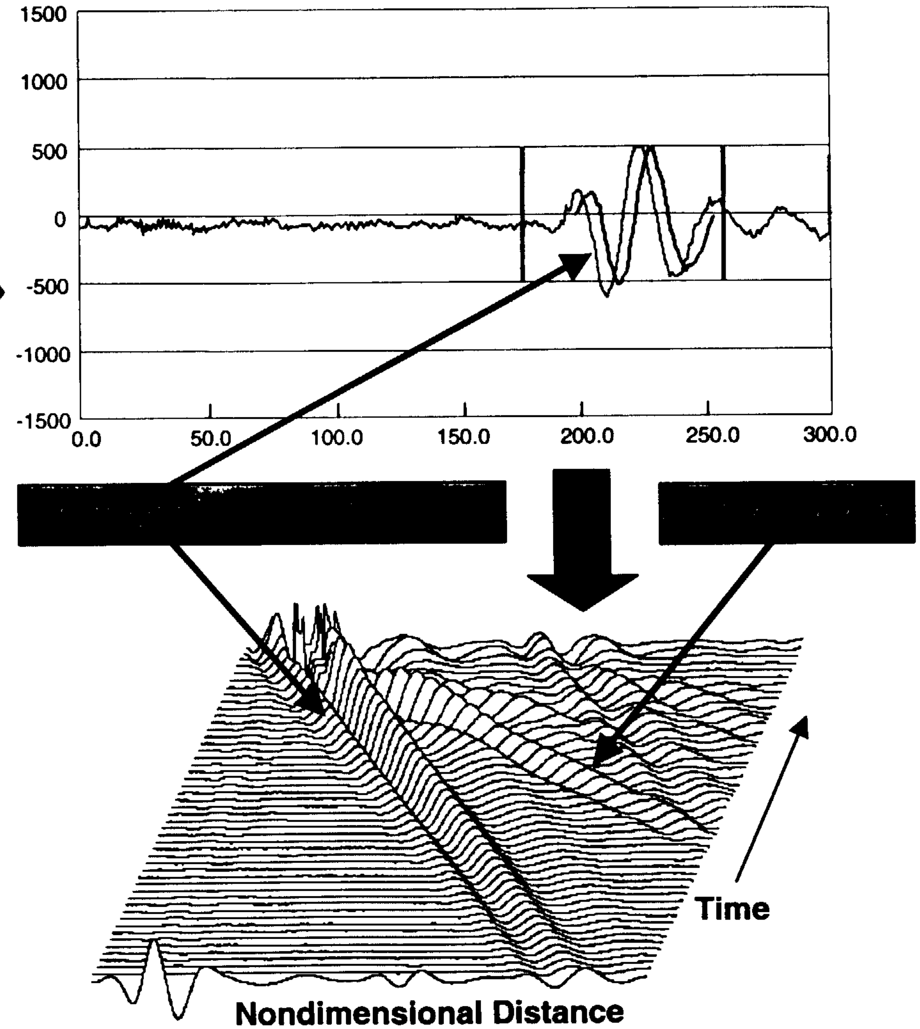


FIVE SEGMENT BOOSTER

Propellant Surface Mapping



Noise Reduction of Acquired Data

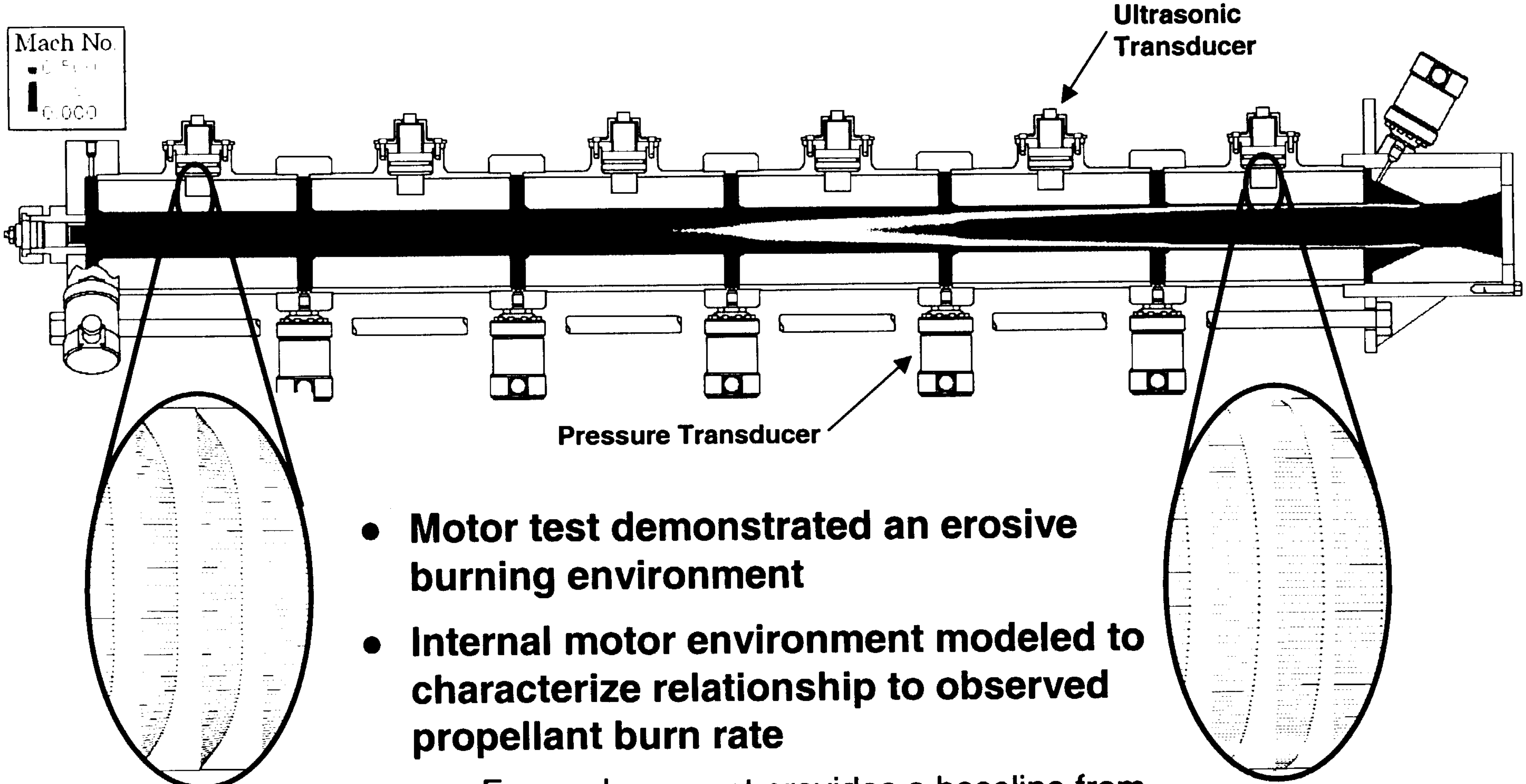


Time History of Propellant Surface Regression

- **Data was acquired every 20 msec with a sample rate of 10 MHz for each of the six segments**
- **Return wave form from the propellant surface is tracked and its time of flight used to establish propellant web thickness**
  - Speed of sound in propellant established through testing in a laboratory environment

FIVE SEGMENT BOOSTER

Subscale Motor Design

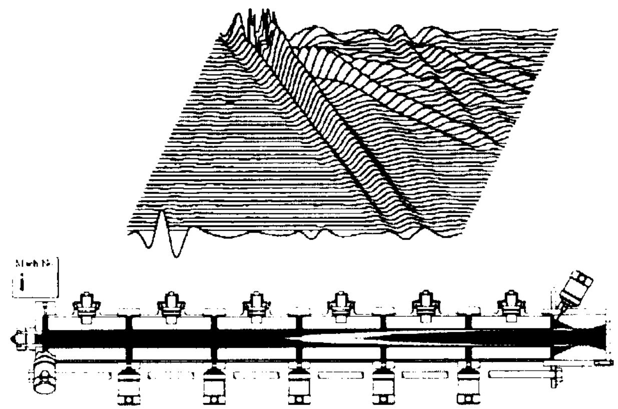


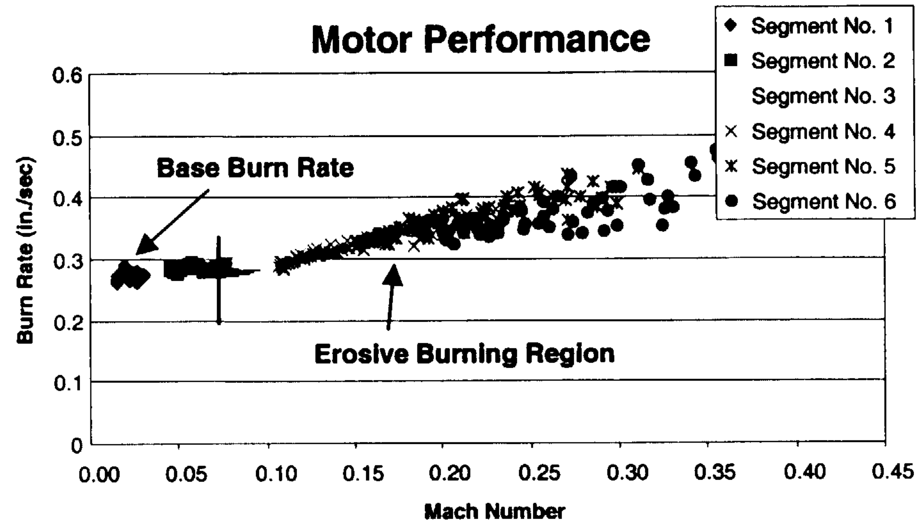
- **Motor test demonstrated an erosive burning environment**
- **Internal motor environment modeled to characterize relationship to observed propellant burn rate**
  - Forward segment provides a baseline from which to compare the other segments

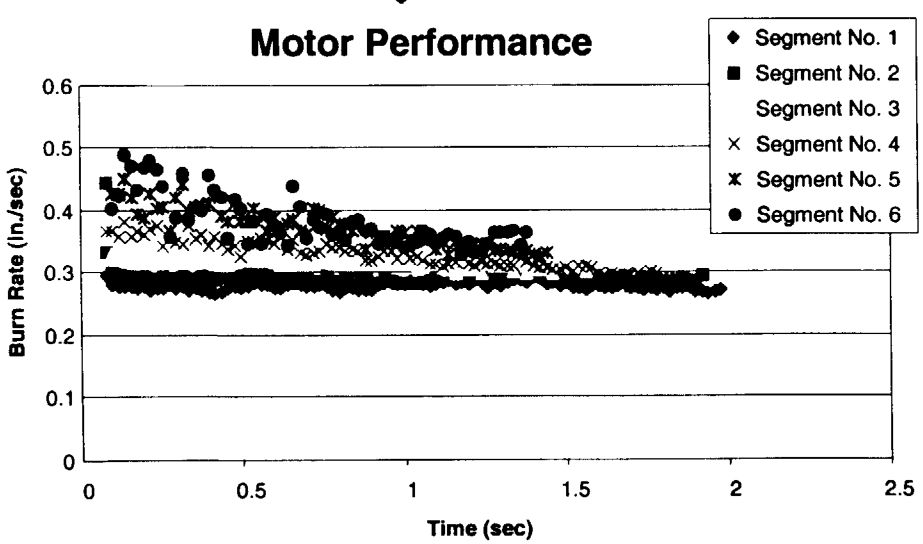
Modeling Assumptions

- **Erosive burning can be characterized through 1-D ballistic analysis techniques**
  - Shown to be accurate through subscale and full-size motor analysis
  - Able to normalize propellant burn rates with respect to axial Mach number
- **Erosive burning is a boundary layer phenomena**
  - Burn rate enhancement can be scaled with an association with grain hydraulic diameter
  - Prior to reaching a threshold, aPn applies. Once the threshold is exceeded, erosive burn rate is influenced by local Mach number
    - The threshold is associated with core fluid flow influencing the near propellant boundary layer

Erosive Burning Characterization







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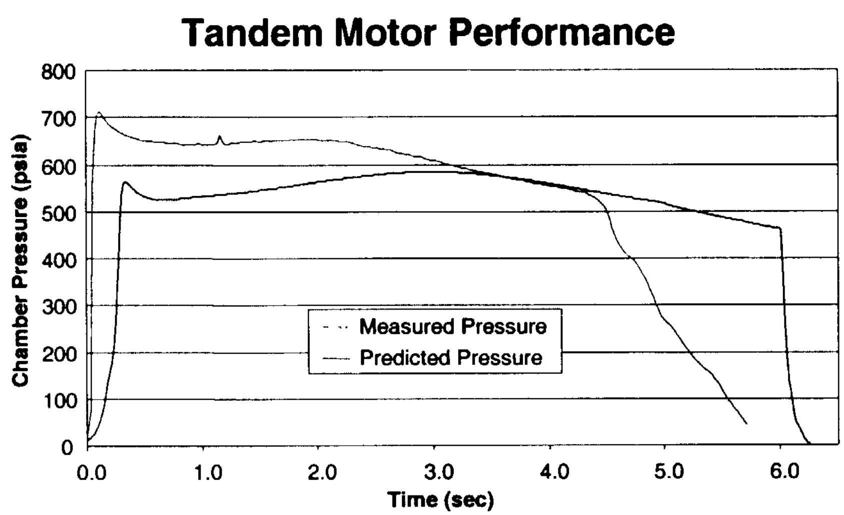
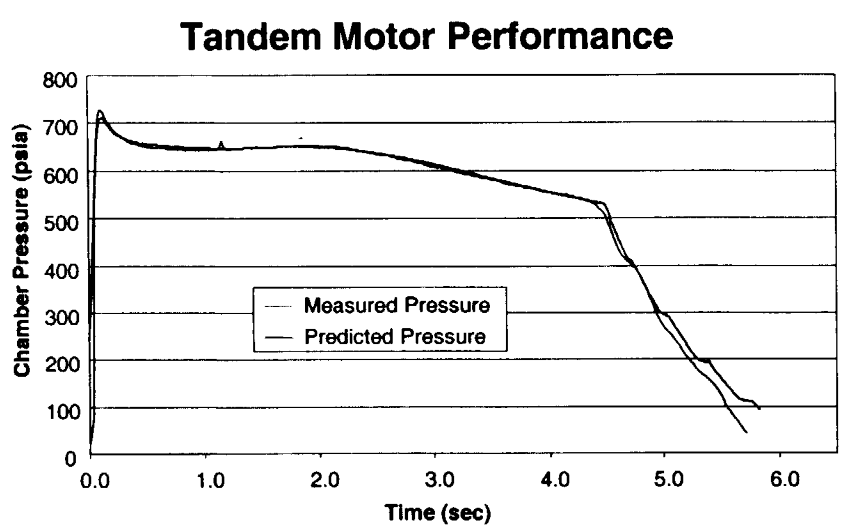
- Erosive burning model is a linear function of Mach number

Tandem Motor Predicted Performance



- Original prediction using data from single motor firing
- No erosive burning



- Re-prediction using measured propellant burn rate
- *Accurate match indicates that measured burn rate captures individual segment performance*

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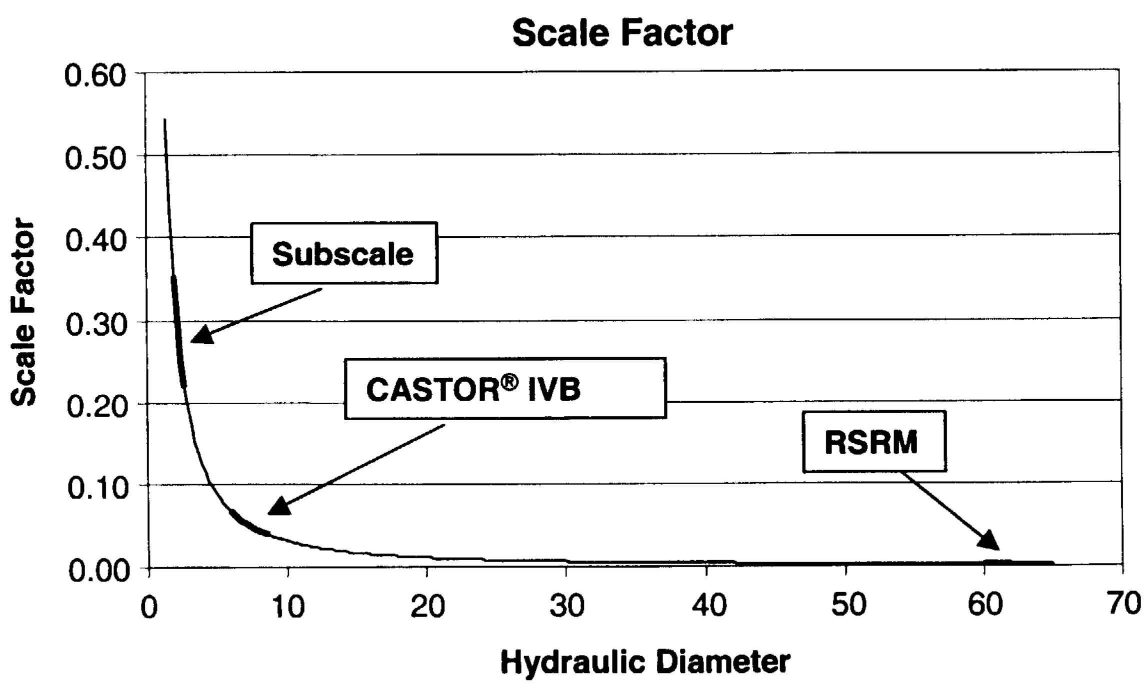
Hydraulic Diameter Influence on Erosive Burning



- Scaling with hydraulic diameter is a means to capture the propellant surface environment in a 1-D analysis
- Scale factor is curve fit from the subscale and full-scale data

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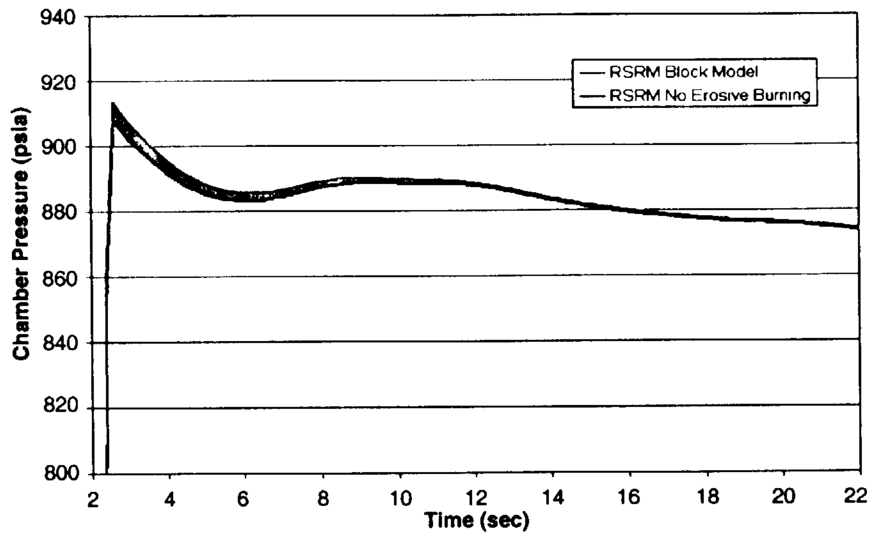
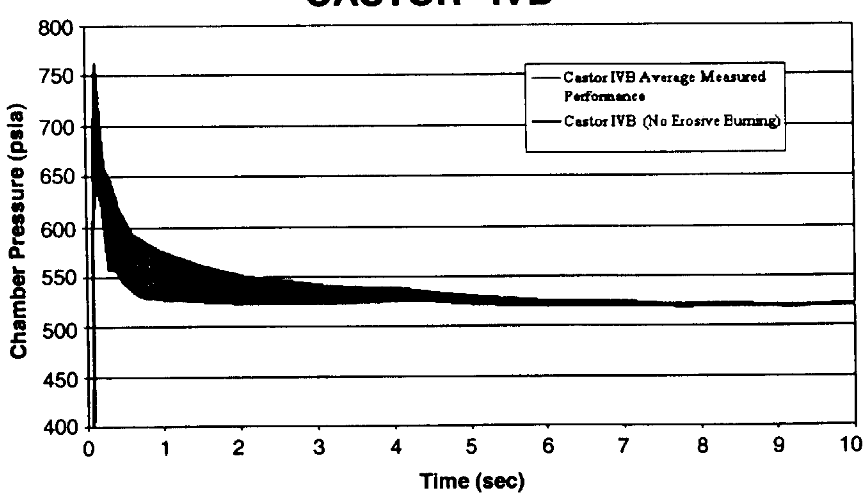
CASTOR® IVB and RSRM Predictions

RSRM Block Model Pressure



- RSRM used as a threshold for the erosive burning model
- Model indicates approximately 6 psi enhanced burn rate present in RSRM

CASTOR® IVB

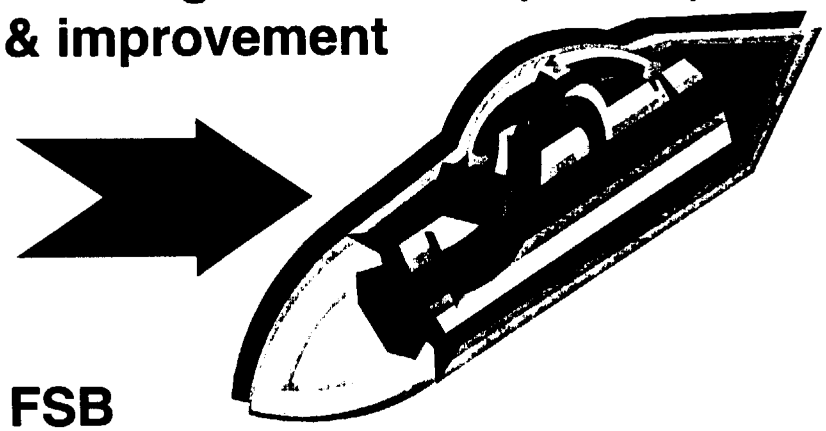


- CASTOR® IVB pressure trace matches well

FIVE SEGMENT BOOSTER

ETM-3: World's Largest Segmented SRM

- **MSFC and Thiokol are well under way with design and verification of a five-segment Engineering Test Motor (ETM-3) — an endeavor focused on learning & improvement**
  - People
  - RSRM (margins)
  - Techniques (models, methods, etc.)

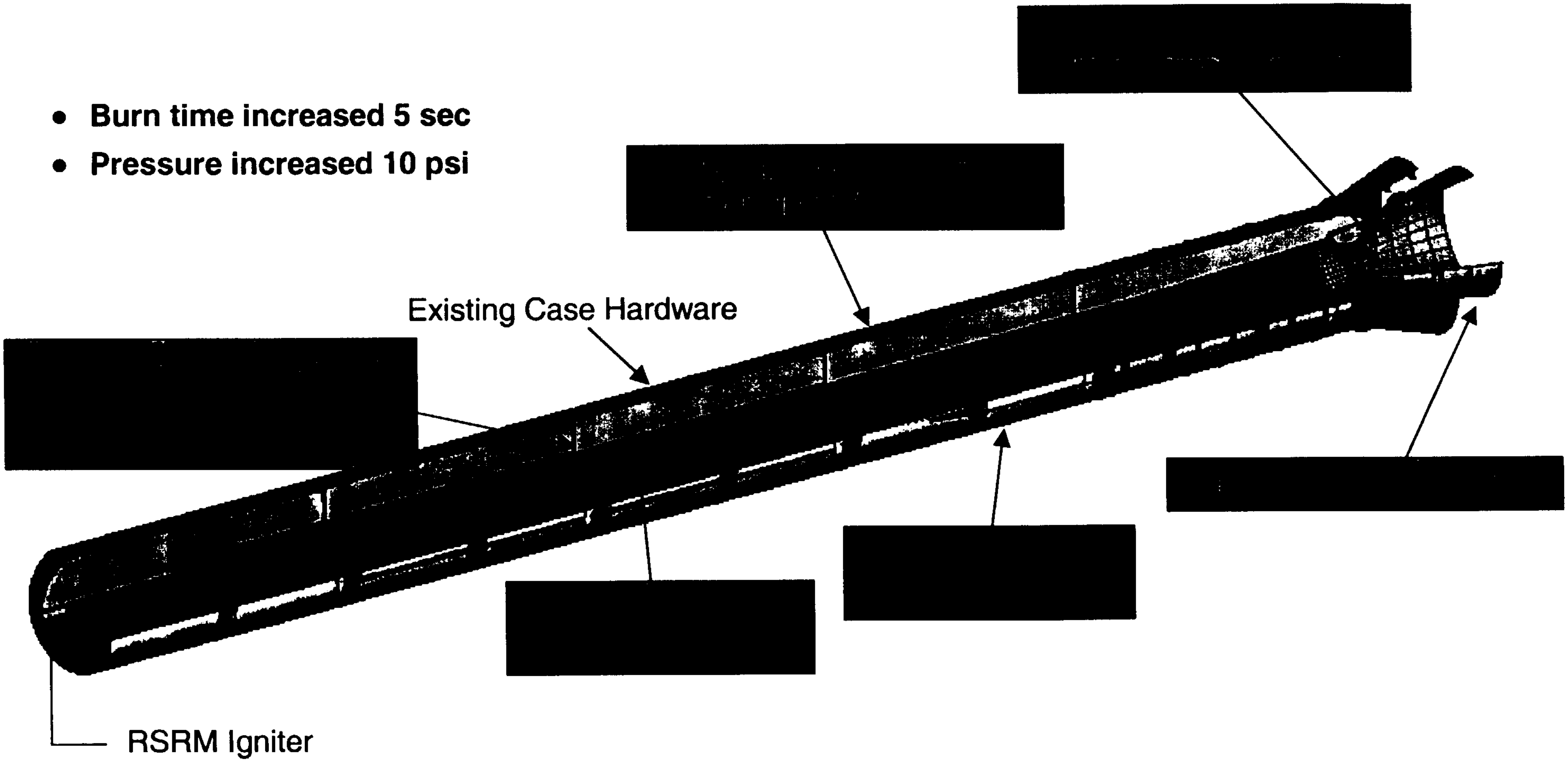


- **ETM-3 provides opportunities for FSB risk reduction and technical skill enhancement**
  - *Erosive burning (validate analytical predictions and scale factors)*
  - Propellant formulation
  - Instrumentation
  - Structures
  - Computational Fluid Dynamics

FIVE SEGMENT BOOSTER

ETM-3 Five-Segment Test Motor

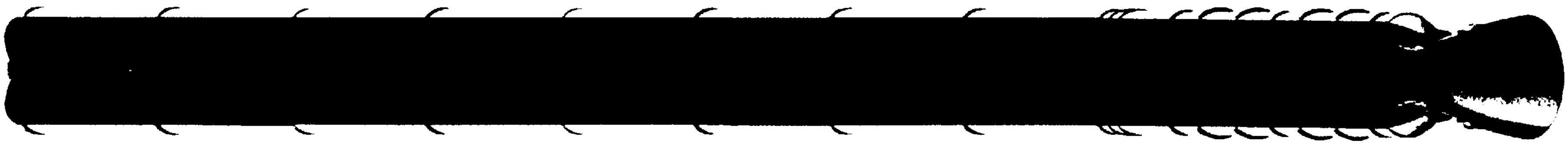
- **Burn time increased 5 sec**
- **Pressure increased 10 psi**



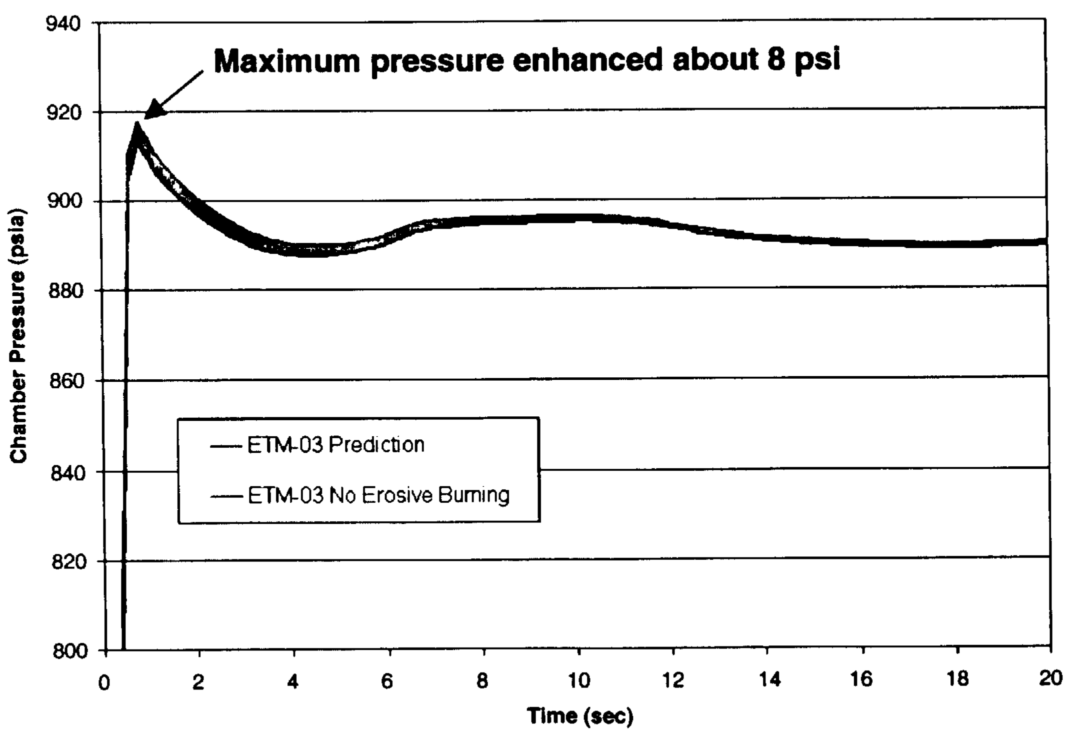
STATIC TEST SCHEDULED JULY 2003

FIVE SEGMENT BOOSTER

ETM-3 Predicted Erosive Burning



ETM-3 Ballistic Performance



- **ETM-3 models predict a burn rate enhancement of about 8 psi due to erosive burning**
- **FSB models predict a burn rate enhancement of less than 30 psi due to erosive burning**

FSB Program Summary

- **FSB shows great potential to enhance Space Shuttle capability**
  - Eliminate RTLS or TAL abort modes
  - Achieve ATO with single engine out off the pad
  - Orbiter space station Alpha payload increased to 40,000 lb
  - Enable crew escape module and other Space Shuttle system reliability and safety upgrades
- **Subscale testing and preliminary analysis show erosive burning to be a non-issue for FSB (less than 30 psi)**
- **Five-segment ETM-3 provides early validation of analytical methods**
  - Increase understanding of internal gas dynamics
  - Improve ignition transient model
  - Demonstration of reduced burn rate propellant ballistic performance
  - Provide data for potential FSB design update and loads refinement